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Technical Report S-217

EFFECT OF INTERIOR BALLISTIC PARAMETERS ON ROCKET EXHAUST SMOKE

by

Daniel W. Placzek
Kenneth J. Martin
Joe M. Viles

July 1969

U. S. ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA 35809

Contracts
DAAH01-68-C-0632
DAAH01-69-C-0772

ROHM AND HAAS COMPANY
REDSTONE RESEARCH LABORATORIES
HUNTSVILLE, ALABAMA 35807

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FOREWORD

The work described in this report was performed under Contract DAAH01-69-C-0772 for exploratory development of propellants for missiles and rockets under the technical cognizance of the Solid Propellant Chemistry Branch, Army Propulsion Laboratory and Center, Research and Engineering Directorate, U. S. Army Missile Command.

This report constitutes a continuing study of smoke in solid propellant rocket exhausts begun under Contract DAAH01-68-C-0632. The investigations were conducted in the controlled environment smoke measurement facility constructed under Contract DAAH01-67-C-0655. The goals of these investigations are an understanding of the kinetics and mechanism of smoke formation and determination of the means available to minimize this signature.

Prior work was reported in Technical Reports S-159, which described the facility, and S-171, which gave results of early comparative observations.

ABSTRACT

A systematic investigation of the effect of interior ballistic parameters on solid rocket propellant exhaust smoke was initiated in a controlled environment smoke measurement facility. Conventional plastisol-nitrocellulose composite propellants were used in this investigation. Highly significant effects on exhaust smoke were found for varying interior ballistic parameters such as chamber pressure, mass discharge rate, and expansion ratio. These results are interpreted in terms of aerosol particle size and concentration as functions of time. Motors were prepared and fired outdoors to demonstrate the results of these studies under field conditions.

CONTENTS

Section I. INTRODUCTION

The presence of visible exhaust can constitute an undesirable or even detrimental feature of a rocket motor. Smoke obscures vision and thereby can prevent human guidance or delay a second firing. Furthermore, a visible exhaust plume clearly indicates the source of a firing, an obvious target for return fire. In some specific applications, these drawbacks become critical. Army and the Redstone Research Laboratories of Rohm and Haas Company have addressed themselves to the pragmatic problems of the evaluation of "smokeless" propellants and the determination and identification of sources and causes of smoke, in order to provide an *a priori* basis for deciding which compositions and conditions yield minimum smoke.

The initial problem encountered in these investigations was the fundamental one of providing a scientific basis for terms such as "smoky". Propellant exhaust can be considered smoky in terms of scatter of incident light. The detector of the scattered light from the exhaust plume may be the human eye or an instrumental detector. Evaluation of human observer sightings, however, engenders complicating physiological considerations which have been enumerated elsewhere (1).[1] Therefore, smoke was evaluated in terms of its extinction (aerosol optical density), thereby eliminating these complicating physiological factors which are amenable to scientific interpretation or definition only with great difficulty. Also, scattering displays a complex dependence on scattering angle (2) and this additional problem was thereby avoided for the initial approach.

Extinction, E, may be defined as follows.

$$E = K_a n\pi r^2 \ell \log e = \ln \frac{i}{i_0},$$

where,

πr^2 = geometrical cross-section of the (assumed), spherical aerosol particles in cm^2,

n = particle concentration (cm^{-3}),

ℓ = path length in cm,

i_0 = incident light intensity,

[1]Numbers in parentheses indicate references at the end of the report.

i = transmitted light intensity, and

K_a is an efficiency factor which displays a functional dependence on wavelength, particle diameter, and index of refraction of the particulate matter relative to the surrounding medium; it is the factor relating optical and geometrical cross-sections. For a monodisperse aerosol, i.e., where the condensed phase consists of particles of equal size, or for a polydisperse aerosol treated as a monodisperse system with an averaged particle diameter, the extinction specifically displays a functional dependence on d/λ, where d is the mean particle diameter and λ is the wavelength of light. Figure 1 is a typical display of such dependence for particles of refractive index $\underline{m}$. By determining the extinction at several (at least three) wavelengths, it is possible to identify the portion of the curve along which measurements lie.[2] Thus, a curve-fitting process can be made to yield a value for the average particle diameter from the abscissa as well as the value of K_a for any particular wavelength from the ordinate. The equation can be used to determine a particle concentration.

The kind of functional dependence portrayed in Figure 1 has some interesting implications. In the small particle regime ($\pi d/\lambda << 1$), K_a decreases rapidly with a decrease in particle diameter, and the extinction decreases accordingly. Thus, if aerosol particles could be made small enough, they could be rendered invisible to the human eye.

In the large particle regime ($\pi d/\lambda >> 1$), the extinction increases as r^2. But if the volume of aerosol or particulate matter remains constant, then the particle concentration, n, decreases as r^3. The net result is again a decrease in extinction. Thus, if the size of the particles in an exhaust plume can be manipulated, the visibility of that plume to the eye can be controlled to some degree.

An excellent pragmatic example of such control was found in an extensive fog modification study (5), wherein artificial fogs were seeded with NaCl crystals. During a period of time after the seeding, the visibility in the study chamber increased by a factor of 2.6 even though the liquid water content in the air increased only slightly. This decrease in extinction was attributed entirely to a change in the drop-size distribution in the direction of larger droplets.

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[2]See reference (3) for the details of the computational methods employed. See reference (4) for computations from the Mie theory; these computed values were used as the standard theoretical values.

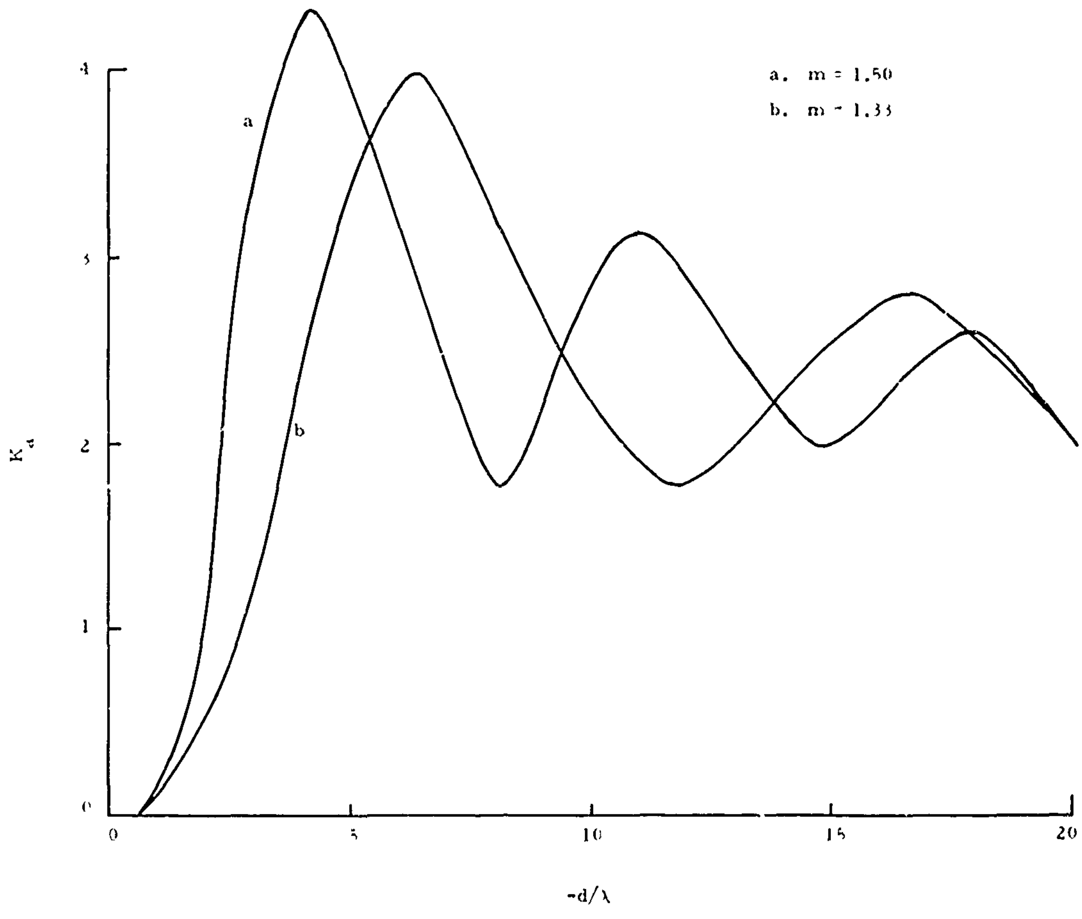

FIGURE 1. DEPENDENCE OF SCATTERING COEFFICIENT, K_a, ON PARTICLE SIZE PARAMETER, $\pi d/\lambda$

Visible rocket exhaust smoke may be divided into two general aerosol categories, volatile and non-volatile. The non-volatile particles may, typically, be unoxidized carbon or they may be oxides derived from common additives such as aluminum, ferrocene, or tin or lead salts. Alternatively, normally gaseous exhaust products may condense to the liquid phase. The prime example here is HCl, a product of the combustion of ammonium perchlorate (AP), which lowers the vapor pressure of water and co-condenses with water, forming an aerosol.

In a real-life situation, the exhaust cloud forms and then dissipates over some measurable time period. A comparable situation obtains within the closed experimental facility used at these Laboratories (described below) — formation, growth, and dissipation of the smoke. However, because of the artificial constraints within the environmental chamber, such as continuous stirring and constant volume, the time period is probably altered. Data in the experimental facility are conventionally acquired for 360 sec; it has been found that this period of time is usually sufficient to encompass the process of smoke growth (i.e., the increase in extinction), the attaining of a maximum in extinction, and the first portion of the dissipation process. These processes, it should be noted, usually occur more slowly than the corresponding out-of-doors process.

Several processes may be involved to explain smoke build-up and dissipation. Smoke formation, in the case of solid particle exhaust, is usually due to the cooling of molten droplets. In the case of a liquid-containing aerosol, formation is due to a nucleation process or to a spontaneous condensation. In a real system wherein nucleating agents are copious, an attempt to differentiate between these condensation processes could well be considered academic. Particles decline in size by evaporation and grow by agglomeration and a continuing condensation process. Additionally, particles settle out of the smoke cloud. In the final analysis, an understanding of the mechanism of smoke build-up and decay is essential in eventually exercising control over smoke.

The mechanism of smoke formation in the $HCl-H_2O$ system initially appears to be a simple one. HCl, a product of AP combustion, reduces the vapor pressure of water vapor in the air, and the HCl co-condenses with the water vapor to form the aerosol. The phase diagram for the H_2O-HCl system is well known, and it is possible to calculate the amount of material that will condense under any given condition of humidity and temperature. Such calculations have indeed been made, and these make the obvious predictions that a minimum humidity value is required for any condensation to occur and that the amount of condensate increases with humidity thereafter. Thus, smoke increases with humidity, a prediction which was readily verified in indoor and outdoor firings.

Although the equilibrium thermodynamic calculations on the vapor-liquid aerosol correctly predicted trends such as the effect of humidity, they proved to be markedly unreliable in properly portraying absolute behavior. Thus, though smoke should not be formed unless the water vapor content of the air has a specific minimum value, in practice some smoke appeared under all circumstances. A reasonable explanation for this finding is not obvious; the smoke may be due to the initiation of condensation in the near vicinity of the nozzle before substantial mixing has taken place. In this respect, it should be noted that a measurable amount of smoke is not recorded in the experimental facility until several seconds after the motor firing. Similarly, it has been noted in outdoor firings that a visible smoke cloud frequently does not appear until the exhaust plume is of substantial size, several seconds after motor burn-out. Thus, application of equilibrium thermodynamics to rocket exhaust smoke measurements was abandoned rather quickly.

In addition to the often predictable consequences of varying atmospheric conditions, the possibility of altered interior ballistic parameters affecting smoke also existed. Early evaluation tests (6) were fired at 1000 psia chamber pressure, a convenient value which is well within the limits of the motor hardware. Any possible effects of altering chamber pressure and burning rate were unknown. Various other parameters that readily lend themselves to adjustment include mass discharge rate, mean residence time, and exhausting pressure.

That gross propellant compositional changes affect smoke is obvious. In fact, the first task undertaken in this facility was the ranking of several candidate smokeless propellants of markedly differing compositions (6). It was then decided to select a few representative propellants and to determine whether a given amount of smoke is a fixed property of a particular propellant. The first propellant so chosen was a conventional plastisol-nitrocellulose formulation, RH-P-426, which contains 45% AP but no metallic or metal-containing additives.

Section II. EXPERIMENTAL FACILITY

An experimental facility was constructed for these and other studies. This 34 m^3 facility is a closed environmental chamber with mixing fans to provide a homogeneous mixture of the rocket exhaust and the air in the facility with a large dilution factor and a long (9.2 m) light path. A detailed description of the facility has been provided elsewhere (1). One minor alteration merits mentioning: the number of filtered light sensors has been increased to eight, three of which are duplicated. These eight sensors are arrayed about the motor, and only if the air — exhaust mixture is homogeneous would the paired sensors yield identical data, thus providing a continuous check on the data and the mixing process.

The sensor filters are relatively broad-band filters with peak transmissions at 0.56, 0.58, 0.76, 0.87 and 0.98 μm. In reducing data, these broad-band transmission curves are treated as if they were delta functions transmitting only at the peak center. The curves all are nearly symmetrical. Details of the instrumentation, including data acquisition techniques, have been treated elsewhere (1).

Most motor firings used Rohm and Haas 2C1.5-4 motors with a $3^{11}/_{16}$-in. grain length. The propellant weight was about 130 g and this amount afforded a dilution factor $\approx$ 250:1 in the facility. In some instances, two or more motors were stacked, and in these cases the web thickness was decreased so that the weight of propellant burned remained at about 130 g. Also, all motors in any one series were loaded with propellant from one batch in order to eliminate small compositional variations.

Section III. EXPERIMENTS USING PROPELLANT WITHOUT METALLIC ADDITIVES

1. Results

The first experiments on the effects of variation of interior ballistic parameters on smoke formation entailed changing chamber pressure by altering the nozzle throat diameter. These particular experiments are advantageous in that a change in chamber pressure is accompanied by a simultaneous change in mass discharge rate, burning rate, and residence time. If it is possible to change the amount of visible smoke by changing interior ballistic parameters, such changes would most likely appear here.

Data are given in Tables I to IV for series of firings under four conditions of humidity and temperature. Tabulated also are the ballistic parameters of concern. The extinction values are reported for the human eye sensitivity curve. Further, it has been found that during the time the aerosol is trapped in the experimental facility, changes may occur in the mean particle diameter, the particle concentration, and the total liquid content of the aerosol. These values were determined at four points during the course of each run — 1.5, 3.0, 4.5, and 6.0 min after motor firing. Since such values were determined by means of tedious manual data reduction processes, the number of such points was limited; four such data sets provide an adequate representation of the "history" of the aerosol development.

The pressure range studied extended from ~0.4 kpsia to ~2.2 kpsia; the upper value was limited by the ability of the experimental facility to withstand the resultant shock wave without damage.

It is evident from Tables I to IV that a significant effect upon smoke indeed was found. The extinction increased with the concomitant increases in chamber pressure, burning rate, mass discharge rate, and residence time. Typically, extinction increased by a factor of two for a five-fold increase in pressure. This increase was due in part to a modest but regular increase in particle diameter; this was accompanied by an increasing value of K_a (see Figure 1). These two effects operate together to increase the extinction. Both the particle number and the volume of condensate per unit volume of aerosol have a relatively large inherent error and were found to change irregularly or not at all.

Table I. Chamber Pressure Studies at 60°F, 45% r.h. (RH-P-426-ai)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
350	400	0.62	0.78	0.13	0.33	6.6	1.2	1.5 min
				0.17	0.36	6.0	1.5	3.0 min
				0.19	0.38	4.7	1.4	4.5 min
				0.20	0.41	2.6	0.9	Max ext: 6.0 min
1100	880	0.89	1.70	0.17	0.37	5.3	1.4	1.5 min
				0.24	0.39	5.6	1.7	3.0 min
				0.26	0.41	4.5	1.6	4.5 min
				0.26	0.45	2.9	1.4	Max ext: 6.0 min
1550	1580	1.09	2.80	0.21	0.37	5.9	1.6	1.5 min
				0.29	0.44	3.6	1.6	3.0 min
				0.32	0.46	3.3	1.7	4.5 min
				0.34	0.47	2.7	1.7	Max ext: 6.0 min
2150	1500	1.19	2.90	0.20	0.38	5.9	1.7	1.5 min
				0.28	0.45	3.4	1.6	3.0 min
				0.32	0.46	3.2	1.6	4.5 min
				0.35	0.50	2.5	1.6	Max ext: 6.0 min

Table II. Chamber Pressure Studies at 95°F, 85% r.h. (RH-P-426-a1)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
400	450	0.62	0.86	0.24	0.36	9.1	2.2	1.5 min
				0.27	0.37	8.0	[illegible]	3.0 min
				0.27	0.40	5.6	1.9	4.5 min
				0.27	0.40	5.6	1.9	Max ext: 4.6 min
				0.27	0.43	3.6	1.5	6.0 min
850	750	0.86	1.45	0.22	0.38	6.0	1.7	1.5 min
				0.29	0.42	4.8	1.8	3.0 min
				0.32	0.43	4.8	2.0	4.5 min
				0.35	0.46	3.8	1.9	Max ext: 6.0 min
950	830	0.87	1.60	0.25	0.38	6.5	1.9	1.5 min
				0.32	0.43	4.6	1.9	3.0 min
				0.36	0.45	3.9	1.9	4.5 min
				0.38	0.49	3.5	2.2	6.0 min
				0.39	0.47	3.6	2.0	Max ext: 7.5 min
1650	1220	1.04	2.35	0.26	0.41	5.0	1.8	1.5 min
				0.31	0.44	4.1	1.8	3.0 min
				0.33	0.44	4.4	2.0	4.5 min
				0.35	0.43	5.2	2.2	Max ext: 6.0 min
1900	1400	1.19	2.70	0.57	0.36	20.	5.0	1.5 min
				0.57	0.37	18.	4.8	3.0 min
				0.58	0.43	8.6	3.6	4.5 min
				0.60	0.51	3.9	2.7	Max ext: 6.0 min

Table III. Chamber Pressure Studies at 55°F, 55% r.h. (RH-P-426-ai)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
600	560	0.69	1.05	0.15	0.34	6.6	1.4	1.5 min
				0.15	0.34	6.6	1.4	Max ext: 1.6 min
				0.14	0.35	5.1	1.2	3.0 min
				0.13	0.40	2.8	0.9	4.5 min
				0.13	0.44	1.7	0.8	6.0 min
1400	1150	0.92	2.20	0.19	0.37	5.2	1.4	1.5 min
				0.22	0.41	3.8	1.4	3.0 min
				0.22	0.42	3.4	1.3	Max ext: 3.7 min
				0.21	0.43	3.1	1.3	4.5 min
				0.20	0.[illegible]	1.9	1.0	6.0 min
1550	1300	0.98	2.50	0.15	0.35	5.4	1.2	1.5 min
				0.17	0.38	4.3	1.2	Max ext: 2.6 min
				0.17	0.40	3.5	1.2	3.0 min
				0.15	0.43	2.0	0.8	4.5 min
				0.12	0.46	1.2	0.6	6.0 min
1700	1270	1.04	2.45	0.26	0.40	5.1	1.7	1.5 min
				0.33	0.44	3.8	1.7	3.0 min
				0.34	0.45	3.5	1.6	Max ext: 4.1 min
				0.32	0.46	3.1	1.6	4.5 min
				0.32	0.49	2.3	1.4	6.0 min
2350	1640	1.14	3.15	0.27	0.42	4.2	1.6	1.5 min
				0.34	0.46	3.3	1.7	3.0 min
				0.36	0.47	2.9	1.6	Max ext: 4.3 min
				0.35	0.48	2.8	1.6	4.5 min
				0.35	0.50	2.4	1.5	6.0 min

Table IV. Chamber Pressure Studies at 70 F, 70% r.h. (RH-P-426-ai)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
550	560	0.69	1.05	0.13	0.32	7.9	1.4	1.5 min
				0.13	0.35	4.1	0.9	3.0 min
				0.13	0.39	2.7	0.8	4.5 min
				0.14	0.40	2.5	0.8	Max ext: 5.0 min
				0.12	0.42	1.8	0.7	6.0 min
800	710	0.80	1.35	0.16	0.38	4.0	1.2	1.5 min
				0.17	0.39	3.5	[illegible]	Max ext: 2.5 min
				0.17	0.40	2.9	1.0	3.0 min
				0.17	0.42	2.3	0.9	4.5 min
				0.17	0.44	1.8	0.8	6.0 min
1150	900	0.94	1.70	0.22	0.41	4.1	1.5	1.5 min
				0.23	0.43	3.2	1.3	Max ext: 2.3 min
				0.23	0.43	3.0	1.2	3.0 min
				0.23	0.46	2.3	1.2	4.5 min
				0.21	0.48	1.7	1.0	6.0 min
1350	1060	1.01	2.05	0.22	0.40	4.5	1.3	1.5 min
				0.24	0.46	2.5	1.2	Max ext: 2.8 min
				0.24	0.46	2.5	1.2	3.0 min
				0.21	0.51	1.3	0.9	4.5 min
				0.18	0.52	1.0	0.7	6.0 min
1850	1300	1.09	2.50	0.30	0.42	4.5	1.8	1.5 min
				0.32	0.48	2.8	1.6	Max ext: 2.5 min
				0.32	0.48	2.6	1.5	3.0 min
				0.32	0.51	2.0	1.4	4.5 min
				0.29	0.48	1.9	1.1	6.0 min
2100	1530	1.14	2.94	0.36	0.44	4.9	2.2	1.5 min
				0.41	0.48	3.3	1.9	3.0 min
				0.42	0.48	3.1	1.8	Max ext: 3.5 min
				0.41	0.50	2.8	1.8	4.5 min
				0.39	0.49	2.7	1.7	6.0 min

The data show that the particle diameter increased while particle concentration (i.e., particle number) decreased during the course of any one experiment. Also, there usually was a trend during the course of an experiment for the total condensed volume to decline. These effects have opposing consequences; thus, simultaneous changes in each of these parameters often are accompanied by only modest change, if any, in extinction.

The data cited above were acquired using propellant made with 5μm AP. Using larger AP, these experiments were repeated over the same pressure range, but with lower burning rate, lower mass discharge rate, and greater residence time. Data are presented in Tables V and VI for the propellant made with 180μm AP. Again extinction increased with increased chamber pressure, burning rate, mass discharge rate, and residence time. Data for both propellants are presented graphically in Figure 2, where it can be seen that the propellant with the fine (ai) grind AP, i.e., the propellant with the higher burning rate, yielded more smoke at the same pressure. These results will be considered in more detail below in the light of succeeding experiments.

In one set of experiments, the mass discharge rate was held constant by controlling chamber pressure and motor length. The burning rate and the residence time were allowed to vary. Results are tabulated in Table VII. Extinction increased dramatically with increased chamber pressure, typically by a factor of two for a three- to four-fold increase in pressure.

The technique of stacking motors also was employed in a series of motor firings wherein the chamber pressure, burning rate, and total mass discharge were maintained the same for motors of differing length and web thickness. The result was a considerable change in mass discharge rate. A modest change in residence time also occurred. Results are compiled in Tables VIII and IX. Extinction decreased as mass discharge rate was increased.

In contradistinction to the previous sets of runs (Table VII) where smoke increased with an increase in residence time, smoke here decreased with an increase in residence time. Thus, although mean residence time may have an effect on smoke, any effect appears to be over-ridden by other factors. Admittedly, it is not surprising that the residence time of normally gaseous species at several thousand degrees Kelvin proves to be irrelevant. Residence time could well have an effect if, for example, it were an important factor controlling afterburning or if combustion efficiency were poor.

Table V Chamber Pressure Studies at 90°F, 60% r.h. (RH-P-426-ac)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
650	200	2.10	0.385	0.04	~0.25	9.9	0.8	1.5 min
				0.04	0.28	4.3	0.5	Max ext 2.9 min
				0.04	0.28	4.3	0.5	3.0 min
				0.04	0.30	3.0	0.4	4.5 min
				0.04	0.34	1.6	0.3	6.0 min
750	220	2.15	0.410	0.05	~0.25	11.8	1.0	1.5 min
				0.06	0.28	6.7	0.8	3.0 min
				0.06	0.32	3.7	0.6	4.5 min
				0.06	0.36	1.9	0.5	6.0 min
				--	-	--	--	Max ext: 3.8-6.0 min
880	240	2.25	0.440	0.05	0.26	8.0	0.7	1.5 min
				0.06	0.31	4.3	0.7	3.0 min
				0.07	0.34	3.5	0.7	4.5 min
				0.08	0.37	2.1	0.6	Max ext 6.0 min
1250	275	2.50	0.530	0.15	0.30	8.2	1.2	1.5 min
				0.16	0.34	4.0	0.8	3.0 min
				0.17	0.39	2.9	0.9	4.5 min
				0.19	0.45	1.8	0.9	Max ext: 6.0 min

Table VI Chamber Pressure Studies at 70°F, 60% r.h. (RH-P-426-ac)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^{5}$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-6}$)	Comments
600	560	2.10	0.380	0.03	~0.25	12.3	1.0	1.5 min
				0.04	0.27	8.5	0.9	3.0 min
				0.04	0.29	7.1	0.7	4.5 min
				0.05	0.33	4.2	0.8	Max ext 6.0 min
1050	520	2.40	0.480	0.0[illegible]	0.28	10.9	1.3	1.5 min
				0.11	0.31	6.[illegible]	1.1	3.0 min
				0.11	0.35	4.3	1.0	4.5 min
				0.12	0.36	2.4	0.6	Max ext 6.0 min

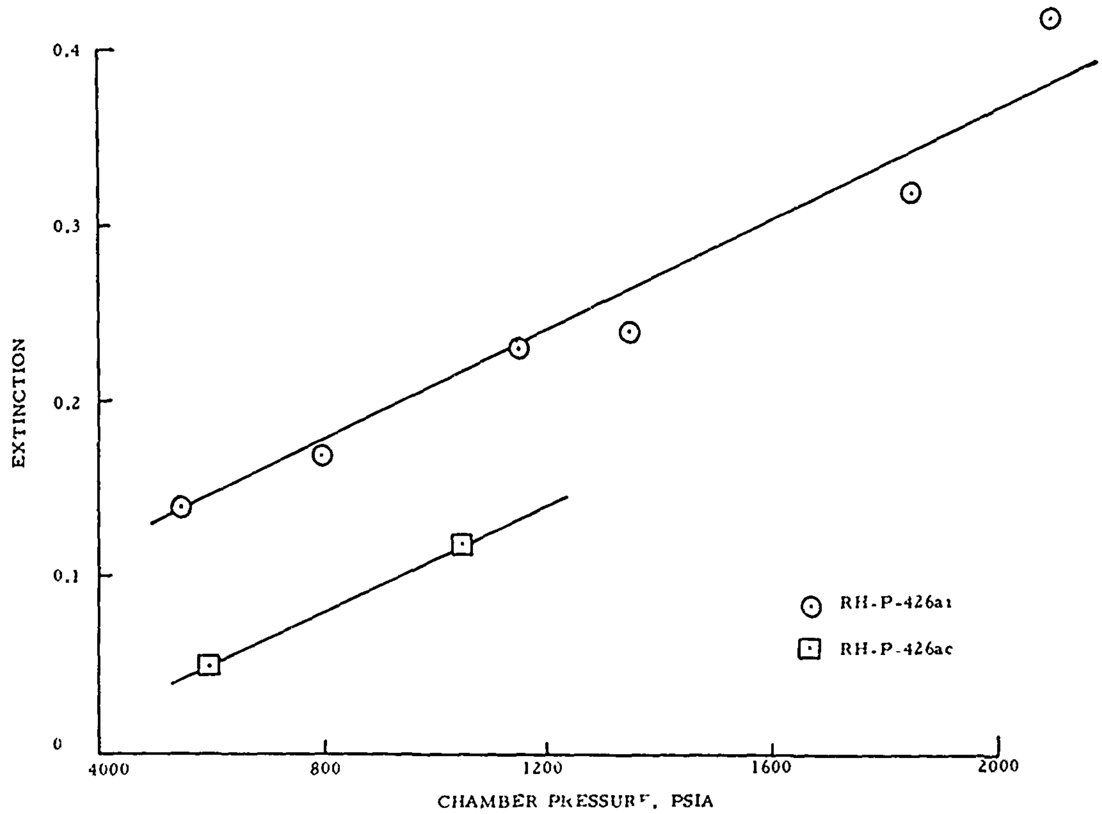

FIGURE 2. EXTINCTION VS. CHAMBER PRESSURE AP-CONTAINING PROPELLANT

Table VII. Residence Time Studies at 90°F, 75% r.h. (RH-P-426-al)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-6}$)	Comments	
1850	1380	1.25	2.65	0.30	0.37	9.2	2.4	1.5 min	1 motor
				0.37	0.38	9.7	2.8	3.0 min	
				0.38	0.39	8.7	2.7	4.5 min	
				0.41	0.40	8.6	2.9	Max ext: 5.1 min	
				0.40	0.40	8.3	2.8	6.0 min	
450	1250	0.70	1.20	0.18	0.38	5.3	1.5	1.5 min	2 stacked motors
				0.22	0.40	4.9	1.6	3.0 min	
				0.22	0.40	4.7	1.6	Max ext: 3.2 min	
				0.21	0.44	2.5	1.1	4.5 min	
				0.21	0.47	2.0	1.1	6.0 min	
1300	1090	1.25	2.10	0.11	0.37	4.4	1.2	1.5 min	1 motor
				0.13	0.38	2.7	0.8	3.0 min	
				0.13	0.39	2.4	0.7	4.5 min	
				0.13	0.39	2.4	0.7	Max ext: 4.6 min	
				0.12	0.42	1.5	0.6	6.0 min	
400	1160	0.70	1.10	0.074	0.40	1.4	0.5	1.5 min	2 stacked motors
				0.094	0.42	1.3	0.4	3.0 min	
				0.11	0.46	1.1	0.6	Max ext: 4.5 min	
				0.11	0.49	0.79	0.5	6.0 min	
1570	1150	1.25	2.20	0.17	0.36	4.6	1.1	1.5 min	1 motor
				0.18	0.38	4.3	1.2	Max ext: 1.6 min	
				0.17	0.39	3.8	1.2	3.0 min	
				0.14	0.40	2.7	0.9	4.5 min	
				0.13	0.43	1.8	0.7	6.0 min	
550	1300	0.70	1.25	0.10	0.40	1.9	0.6	1.5 min	2 stacked motors
				0.10	0.41	1.6	0.6	Max ext: 1.8 min	
				0.10	0.43	1.2	0.5	3.0 min	
				0.096	0.46	0.88	0.4	4.5 min	
				0.097	0.46	0.87	0.4	6.0 min	

Table VIII. Mass Discharge Rate Studies at 75°F, 80% r.h. (RH-P-426-ac)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^{5}$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-6}$)	Comments	
1050	250	2.5	0.48	0.28	0.31	12.2	1.9	Max ext: 3.0 min	1 motor
				0.27	0.33	9.8	1.8	4.5 min	
				0.26	0.35	7.7	1.7	6.0 min	
1100	510	3.0	0.49	0.24	0.35	9.1	2.0	Max ext: 3.0 min	2 motors
				0.24	0.36	7.4	1.8	4.5 min	
				0.23	0.37	6.2	1.6	6.0 min	
1000	810	3.3	0.47	0.17	0.31	13.5	2.1	1.5 min	3 motors
				0.18	0.32	10.4	1.8	Max ext: 2.0 min	
				0.16	0.34	7.7	1.6	3.0 min	
				0.12	0.36	4.0	1.0	4.5 min	
				0.09	0.39	2.0	0.6	6.0 min	

Table IX. Mass Discharge Rate Studies at 95°F, 70% r.h. (RH-P-426-ac)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments	
1100	265	2.5	0.51	0.10 0.14 0.14 0.15	0.27 0.29 0.31 0.32	16.1 12.7 10.6 8.1	1.7 1.6 1.6 1.4	1.5 min 3.0 min 4.5 min Max ext: 6.0 min	1 motor
1100	530	3.0	0.51	0.09 0.11 0.11 a	0.29 0.32 0.36 a	9.7 6.2 3.5 a	1.2 1.1 1.0 a	1.5 min 3.0 min Max ext: 4.5 min 6.0 min	2 stacked motors
1200	870	3.3	0.50	0.10 0.11 0.11 0.11	0.27 0.30 0.33 0.38	12.6 7.1 5.5 3.0	1.3 1.0 1.0 0.9	1.5 min 3.0 min 4.5 min Max ext: 6.0 min	3 stacked motors

[a] Data lost after 1.5 min.

In summation, the above studies clearly indicate that smoke increases with an increase in chamber pressure or burning rate, and decreases with an increase in mass discharge rate; the chamber pressure and burning rate effects predominate. It is not possible to assess the effect, if any, of the mean residence time.

In view of these results, it is now possible to consider those studies wherein the burning rate was changed by changing AP grind. Figure 2 shows that the effect is not due solely to pressure. On the other hand, these differing data cannot be correlated solely on a burning rate-cum-mass discharge rate basis. A plot of extinction vs. burning rate (or mass discharge rate) yields two approximately straight lines of differing slope that do not intersect. Smoke thus increases with both pressure and burning rate.

Finally, the effect of changing the pressure of the exhaust gases was determined. The motors employed in the studies discussed above were equipped with conventional convergent—divergent nozzles with a 15° half-angle divergence. The ratio of the exit area to throat area provided theoretical expansion to atmospheric pressure. In thes experiments to determine the effect of exit pressure, nozzles of this same design were used, but the nozzle length was adjusted so as to under or overexpand the exhaust gases by a factor of two. Other variables were maintained constant. The underexpanded nozzle yielded less smoke than the overexpanded nozzle; the nozzle designed to expand to atmospheric pressure gave an intermediate value (Tables X and XI). The differences observed were as much as a factor of two.

2. Discussion

Despite limitations of experimental error, general trends may be noted in these experiments. For example, after a motor firing, the trapped aerosol tends to exhibit particle growth, decline in particle number, and decline in the total amount of liquid aerosol. Often these factors change simultaneously and extensively while the extinction in the visible region changes little after its initial buildup; the principal change is observed in the near-infrared, where the wavelength of light is approximately πd. In addition, in the $HCl-H_2O$ system, lower extinction values are, in general, marked by smaller particle size and the condensation of a lesser amount of liquid as the aerosol phase. Furthermore, maximum particle concentration and condensed aerosol volume but minimum particle size and minimum extinction are usually recorded at very short time. However, calculations show that in these cases equilibrium lies in the direction of less aerosol and of net

Table X. Exit Pressure Studies at 95°F, 75% r.h. (RH-P-426-al)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^5$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments	
950	830	0.78	1.60	0.24	0.34	11.0	2.3	1.5 min	Overexpanded by factor of 2
				0.27	0.43	3.8	1.6	3.0 min	
				0.30	0.45	3.3	1.6	4.5 min	
				0.31	0.47	2.7	1.5	Max ext: 6.0 min	
1000	860	0.81	1.65	0.34	0.31	24.9	3.9	1.5 min	Optimum Expansion
				0.41	0.36	15.3	3.7	3.0 min	
				0.44	0.38	12.3	3.6	4.5 min	
				0.45	0.41	8.2	3.0	Max ext: 5.8 min	
				0.45	0.41	8.2	3.0	6.0 min	
1100	880	0.85	1.70	0.37	0.31	25.6	4.0	1.5 min	Underexpanded by a factor of 2
				0.50	0.33	25.6	4.8	3.0 min	
				0.56	0.37	17.8	4.7	4.5 min	
				0.60	0.38	16.7	4.8	Max ext: 6.0 min	

Table XI. Exit Pressure Studies at 75°F, 60% r.h. (RH-P-426-ai)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction	Particle Size (μm)	Particle Number (cm^{-3} × 10^{5})	Condensed Phase Vol/Unit Aerosol Vol (× 10^{-9})	Comments	
950	830	0.78	1.60	0.24 0.30 0.32 0.33 0.33	0.31 0.35 0.44 0.46 0.47	21.1 12.1 4.2 3.3 3.2	3.3 2.7 1.9 1.7 1.8	1.5 min 3.0 min 4.5 min Max ext: 5.2 min 6.0 min	Overexpanded by a factor of 2
1000	860	0.81	1.65	0.26 0.32 0.34 0.36	0.31 0.36 0.38 0.43	17.8 11.6 8.9 5.3	2.8 2.8 2.6 2.2	1.5 min 3.0 min 4.5 min Max ext: 6.0 min	Optimum expansion
1100	885	0.85	1.70	0.31 0.37 0.40 0.41	0.32 0.33 0.35 0.40	19.7 18.9 14.9 8.3	3.4 3.6 3.4 2.8	1.5 min 3.0 min 4.5 min Max ext: 6.0 min	Underexpanded by a factor of 2

evaporation. If, in the field, exhaust could be dissipated very rapidly, evaporation would be accelerated and particle growth by condensation or coalescence would be minimized; the result would be less visible smoke. The phenomenon of increasing visible smoke density for significant time after burn-out has been observed in most field firings. Several series of motors were fired in the field, and the results have been compared to tunnel firings. The results are presented and discussed in the Appendix.

Several observations have a strong influence on any mechanism postulated for aerosol development. Among these are the usual facts that no visible smoke is present for the first few seconds after the motor firing and that the maximum amount of smoke is not seen until some time after motor burn-out. Evidently, an effect occurring prior to the appearance of visible smoke is responsible for the different nature of the resulting aerosol clouds. One possible explanation is that sub-visible aerosol particles are formed initially and that these subsequently grow to visible size (7). Ostensibly, the mixing process dictates the nature of the sub-visible aerosol, i.e., particle size and number. Aerosol formation may occur by either homogeneous or heterogeneous nucleation. Although a posteriori evidence indicates that particle growth on a microscopic basis is an energetically more favorable process than evaporation, macroscopic equilibrium thermodynamics predicts the latter under these experimental conditions. However, equilibrium thermodynamics does dictate the eventual evaporation and dissipation of the liquid aerosol.

The net particle growth with simultaneous particle number diminution can be explained by a particle coalescence effect or by concomitant evaporation of smaller particles and condensation onto larger particles; these latter are a pair of energetically favorable processes (8). The fact that the condensed phase volume decreases during the course of a run indicates that some evaporation is taking place. Evaporation eventually becomes the dominating mechanism. The dominant factor in smoke formation appears to be the manner in which the exhaust mixes with the air.

3. Demonstration Motor Firings

In order to provide a demonstration of the conclusions resulting from these studies in the experimental facility, outdoor firings of motors designed to yield either very little smoke or a substantial quantity of smoke were carried out using the same propellant composition, RH-P-426. The interior ballistic specifications of these motors lay within the ranges explored in the tunnel facility studies.

A 2C1.5-4 motor was used for maximum smoke production and a 2C1.75-8 motor was used for the minimum smoke condition; each contained 130 g of propellant. The former had a high chamber pressure, a relatively fast burning rate, and an overexpanded nozzle. The latter had a low chamber pressure, a slow burning rate, and an underexpanded nozzle. The actual values of the ballistic parameters are tabulated in Table XII.

Table XII. Controlled Smoke Density Conditions for Outdoor Firings

Parameter	Maximum Smoke	Minimum Smoke
Chamber pressure	2430 psia	600 psia
AP size	5-8μm	180 μm
Burning rate	2.7 in.	0.37 in./sec
Mass discharge rate[a]	1400 g/sec	390 g/sec
Residence time	1.2 msec	2.2 msec
Exit pressure	0.8 atm	1.5 atm

[a] Increasing mass discharge rate decreases smoke; however, pressure and AP-size effects are more dramatic than mass discharge rate. Therefore, mass discharge rate was made a dependent variable.

The two firings were carried out consecutively, within 10 min of each other. Ambient conditions were 66°F and 86% relative humidity. The motor was fired with the axis of the motor at 15° from the horizontal. Movies of the firings were made, and stills of the two firings at burn-out and at 3 sec and 6 sec after burn-out are shown in Figures 3, 4, and 5, respectively. As illustrated, the experiment was successful in demonstrating the extrapolation of data obtained in the smoke measurement facility to field conditions.

FIGURE 3. PHOTOGRAPHS OF OUTDOOR FIRINGS OF MOTORS LOADED WITH 0.3 LB RH-P-426 PROPELLANT AND PREPARED TO YIELD MINIMUM (UPPER PHOTO) AND MAXIMUM (LOWER PHOTO) SMOKE. AMBIENT CONDITIONS WERE 67°F AND 87% r.h. PHOTOGRAPHS TAKEN AT BURN-OUT

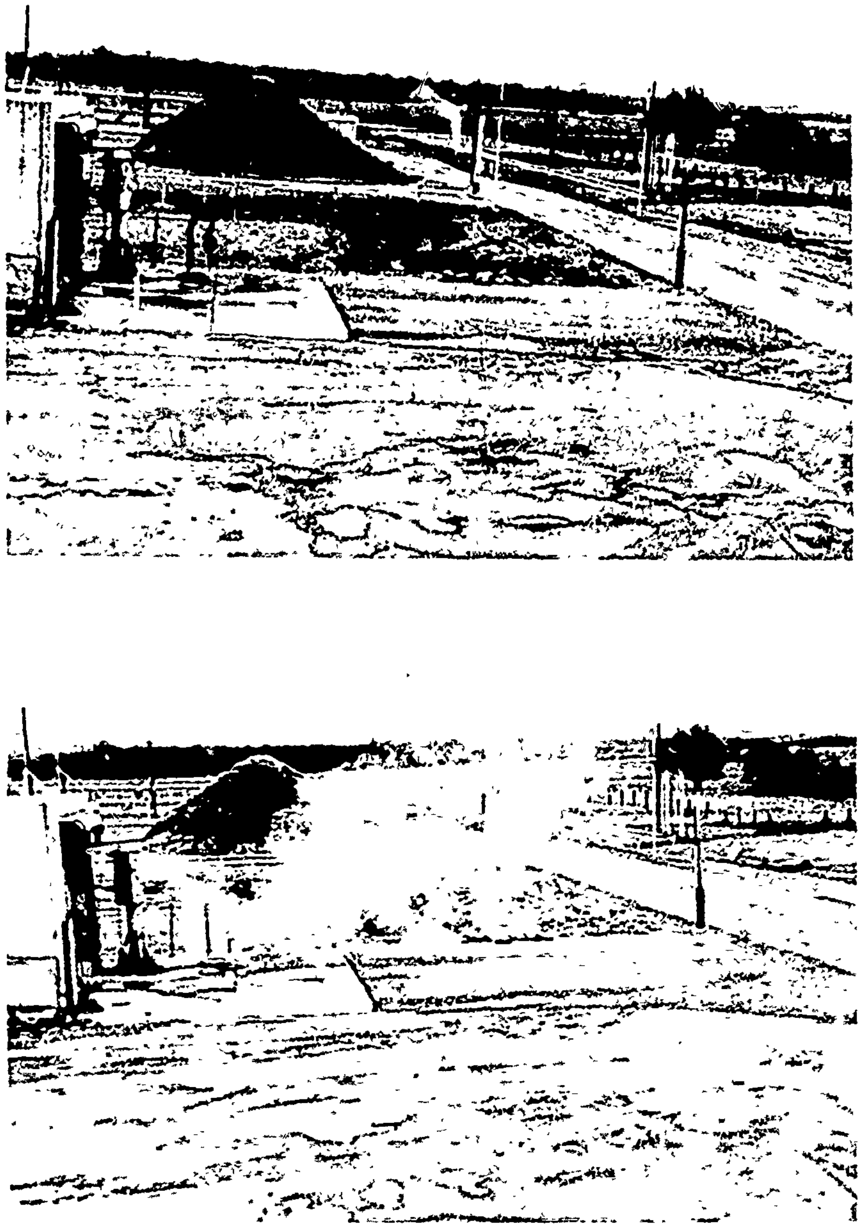

FIGURE 4. PHOTOGRAPHS OF OUTDOOR FIRINGS OF MOTORS LOADED WITH 0.3 LB RH-P-426 PROPELLANT AND PREPARED TO YIELD MINIMUM (UPPER PHOTO) AND MAXIMUM (LOWER PHOTO) SMOKE. AMBIENT CONDITIONS WERE 67°F AND 87% r.h. PHOTOGRAPHS TAKEN 3 SEC AFTER BURN-OUT

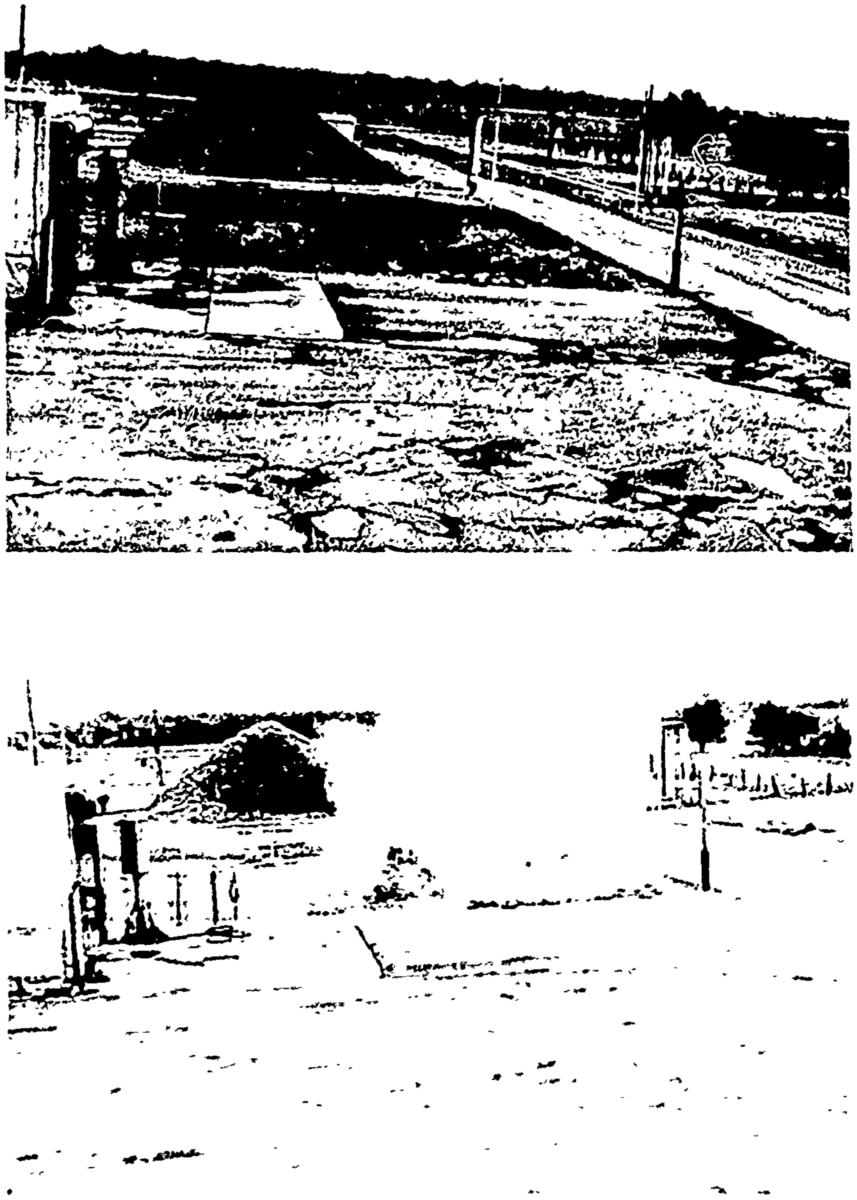

FIGURE 5. PHOTOGRAPHS OF OUTDOOR FIRINGS OF MOTORS LOADED WITH 0.3 LB RH-P-426 PROPELLANT AND PREPARED TO YIELD MINIMUM (UPPER PHOTO) AND MAXIMUM (LOWER PHOTO) SMOKE. AMBIENT CONDITIONS WERE 66°F AND 86% r.h. PHOTOGRAPHS TAKEN 6 SEC AFTER BURN-OUT

Section IV. EXPERIMENTS USING ALUMINIZED PROPELLANT

1. Results

An entirely different kind of problem is encountered when the propellant contains a metallic compound or metal salt and the exhaust contains the corresponding metal oxide. In such cases the exhaust contains a specific amount of solid material, the amount being determined by the weight of metal in the propellant. Since the amount is fixed, the extinction can be altered only within a relatively limited degree by changing the particle size of the metal oxide.

The propellant employed in these studies was RH-P-163, which is RH-P-426 with 1% aluminum added. Large size oxidizer for low burning rate and very low humidity conditions assured that the smoke resulting from the AP (i.e., $H_2O - HCl$) in the propellant would be minimal since it had been found experimentally that the aluminum-free propellant does indeed give negligible smoke under these conditions.

In these experiments, the extinction rapidly attained a maximum and then decreased slowly as the aluminum oxide particles settled out. The data reported below refer to the point of maximum extinction. In order to determine particle diameter and particle concentration, it was assumed that all the aluminum was converted to aluminum oxide and that $K_a = 2$ (3). The Al_2O_3 mean particle diameters determined in these studies were the order of 1 to 2 μm. Thus, extinction is virtually independent of wave length of the light used in these studies.

Motors were fired at various combustion chamber pressures in order to determine whether concomitant changes in pressure, burning rate, mass discharge rate, and residence time can affect smoke. Results are tabulated in Table XIII. As pressure increased the particle size of the aluminum oxide increased, and the extinction correspondingly decreased. By reducing the chamber pressure from 2 kpsia to 0.5 kpsia and correspondingly reducing the burning rate by a factor-of-two, the extinction was increased by about one-third. Similar results were found elsewhere (9), i.e., increasing particle size with increasing pressure.

A set of stacked motors was fired at the same pressure as a single motor in order to alter the mass discharge rate drastically; the concomitant modest change in residence time was unavoidable. Nonetheless, the factor-of-two change in mass discharge rate resulted in no significant change in extinction or mean particle diameter (Table XIV).

Table XIII. Chamber Pressure Studies at Low Humidity Conditions (RH-P-163-ac)

Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction (at onset of run)	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^4$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
540[a]	185	1.8	0.35	0.39	0.67	12.5	2.0	
550[a]	360	2.2	0.35	0.42	0.62	15.8	2.0	2 motors stacked
1000[a]	250	2.5	0.47	0.34	0.75	8.9	2.0	
1150[a]	300	2.6	0.55	0.34	0.77	8.2	2.0	
1400[a]	300	3.1	0.56	0.32	0.81	7.1	2.0	
2150[a]	330	3.5	0.74	0.30	0.87	5.7	2.0	
[illegible][b]	170	1.8	0.32	0.39	0.68	12.0	2.0	
[illegible][b]	360	2.2	0.35	0.43	0.60	16.9	2.0	2 motors stacked
[illegible][b]	240	2.5	0.46	0.33	0.80	7.4	2.0	
[illegible][b]	290	2.6	0.44	0.32	0.81	7.1	2.0	
[illegible][b]	310	3.1	0.59	0.27	0.98	4.0	2.0	
[illegible][b]	360	3.5	0.68	0.29	0.90	5.2	2.0	

[a] 7[illegible] F, 35% r.h.
[b] 7[illegible] F, 20% r.h.

Table XIV Mass Discharge Rate Studies at Low Humidity Conditions (RH P-163 ac)

Temp (°F) Relative Humidity	Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction (at onset of run)	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^{6}$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-6}$)	Comments
95°, 35%	1150	300	2,6	0,55	0,34	0,77	8,2	2,0	
95°, 35%	1200	590	3,1	0,56	0,35	0,75	8,9	2,0	2 motors
70°, 20%	1150	230	2,6	0,54	0,32	0,81	7,1	2,0	
70°, 20%	1300	570	3,1	0,55	0,33	0,79	7,6	2,0	2 motors

Also, a pair of motors was stacked and fired at pressures yielding the same mass discharge rate as a single motor. The mean residence time was altered about 50% thereby. Unfortunately, such a change is brought about by changing the chamber pressure by several hundred percent. The extinction consequently changes (Table XV). Within experimental error, such changes can be attributed solely to burning rate–pressure effects. The stacked motor results are also included in Table XIII where they appear within the content of burning rate effects.

2. Discussion

A great deal of confusion exists in the area of the combustion of aluminum-containing propellants (10). The primary problem is the vastly differing data acquired by different researchers. Measurements of Al_2O_3 mean particle diameters range from ~0.5 to ~5μm. The data reported here are in the lower end of this range. Since they are based on an in situ mode of data acquisition which precludes sampling errors, it is felt that these data are reasonably reliable.

The mechanism most often quoted for production of small diameter Al_2O_3 is vapor condensation in the reaction zone. In such a case, the variables which would affect particle size, and hence visible smoke, are chamber pressure, residence time, and motor size (11). The pressure effect is expected since concentration of condensable oxide in the combustion chamber is a function of pressure. Also, a greater mean residence time allows the condensation process to proceed further and thus increase mean particle size.

The results obtained here agree in part with these conclusions. The effect of pressure was indeed found. The effect of residence time (Table XIII, first two lines of data) was within experimental error, but the effect of residence time found in the referenced studies occurred in a different residence time range. In order to determine the extent of agreement, larger motors would be required. In essence, these data do not disagree with those found previously, and the limited data obtained to date can be interpreted in terms of the vapor condensation mechanism.

Table XV. Residence Time Studies at Low Humidity Conditions (RH-P-163-ac)

Temp (°F), Relative Humidity	Chamber Pressure (psia)	Mass Discharge Rate (g/sec)	Residence Time (msec)	Burning Rate (in./sec)	Extinction (at onset of run)	Particle Size (μm)	Particle Number ($cm^{-3} \times 10^{4}$)	Condensed Phase Vol/Unit Aerosol Vol ($\times 10^{-8}$)	Comments
95°, 35%	550	360	2.2	0.35	0.42	0.62	15.8	2.0	2 motors
95°, 35%	2150	390	3.5	0.74	0.30	0.87	5.7	2.0	
70°, 20%	550	360	2.2	0.35	0.43	0.60	16.9	2.0	2 motors
70°, 20%	2000	360	3.5	0.68	0.29	0.90	5.2	2.0	
70°, 20%	600	400	2.2	0.38	0.46	0.56	2..4	2.0	2 motors
70°, 20%	1950	370	3.5	0.70	0.28	0.94	4.5	2.0	

Section V. CONCLUSION

The studies reported herein represent the first phase of a systematic study of the causes of smoke, i.e., visible propellant exhaust. While the experimental smoke measurement facility has displayed utilitarian functionality in determining the effect of gross compositional changes (6), it has also been used successfully to show that some control can be exercised over the visibility of the exhaust smoke by control of interior ballistic parameters. Thus, a specific amount of smoke is not necessarily an inherent property of a specific propellant formulation.

In general, dramatic alterations in smoke from a given propellant are the result of drastic changes in interior ballistic parameters. The extent to which alterations in smoke can be introduced in a given motor design is a direct function of prescribed missile system limitations. If system design specifications are very restrictive, the ability to reduce smoke is correspondingly restricted. On the other hand, in many cases the smoke produced can be construed as another adjustable parameter, allowing trade-offs within limits to be determined experimentally for any particular propellant. These studies have made evident such possibilities. The generality of these conclusions is the subject of current investigations.

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APPENDIX

OUTDOOR SMOKE FIRINGS

An evaluation program conducted at these Laboratories wherein several propellants were ranked as to their smokiness in an experimental facility (6) has shown that controlled environment chamber experiments are an excellent means of comparing on a common basis the relative smokiness of different propellants. However, no attempt was made to extrapolate or scale the small motor data obtained in the experimental facility to large motors fired in the field. A series of experiments was conducted, concurrently with the experiments discussed in the main text, to compare visual observations of smoke produced outdoors to smoke measurements made in the controlled environment chamber.

The relative smokiness of five propellants was evaluated in 6-in.-diameter motors fired outdoors under a variety of meteorological conditions and in 2-in.-diameter motors fired in the controlled environment chamber under similar temperature and humidity conditions. The outdoor firings were made in volleys of four 6C5-11.4 motors, one each containing RH-U-126 (NF smokeless), RH-P-543 (XLNC smokeless), RH-C-160 (CTPB, 80% AP), and RH-P-161 (PNC, AP, 10% Al for contrast) and one 6 × 6-in. motor containing PNJ (smokeless, cast double-base).[3] Relative rankings of the outdoor firings were based on visual observations by several observers and movies (color and black and white).

The NF composition was least smoky under all conditions. The XLNC and double-base compositions were slightly more smoky than the NF with smoke densities relatively independent of humidity. At low humidities the CTPB composition was comparable to the XLNC and double-base compositions, whereas at high humidities it was as bad as the aluminized composition which produced copious quantities of smoke at all conditions. The data are summarized in Table XVI, and photographs of two outdoor firings are shown in Figure 6.

Correspondence between the outdoor and controlled environment chamber data was qualitatively satisfactory. Good agreement was

[3]Propellant compositions are given in reference (12).

Table XVI. Smoke Comparison Shots — Tunnel and Field Evaluation

	RH-U-126	RH-PXL-543	PNJ	RH-C-160	RH-P-161	Temp. (°F)	r.h. (%)
Observer ranking[a]	1.1	2.8	2.4	3.6	5.0	23	68
Movie evaluation[b]	1	4	2	15	20	23	68
Extinction, tunnel evaluation	c	c	c	c	c	c	c
Observer ranking	1	3.2	2.3	3.2	5	39	43
Movie evaluation	1	4	3	3	20	39	43
Extinction, tunnel evaluation	0.11	0.26	0.21	0.86	∞	48	39
Observer ranking	1.2	1.8	1.8	3.2	5	39	67
Movie evaluation	1	5	3	10	20	39	67
Extinction, tunnel evaluation	0.15	0.25	0.36	1.0(2)[d]	∞	44	67
Observer ranking	2.5	2.2	2.0	5	4	64	84
Movie evaluation	1	3	3	30	20	64	84
Extinction, tunnel evaluation	0.17	0.28	0.48(2)	1.6[e]	∞[e]	67	72
Observer ranking	1.1	3.7	2.7	2.8	5.0	87	32
Movie evaluation	1	4	2	2	20	87	32
Observer ranking	1.1	3.5	2.9	2.2	5.0	80	29
Movie evaluation	1	6	2	2	20	80	29
Extinction, tunnel evaluation	0.09	0.25	0.29(3)	0.49(4)	∞	85	34

[a] The observers ranked the smoke from the five simultaneous firings as 1 through 5 with 1 being the least smoky and 5 being the smokiest firing; the listed values are the average of the observers' rankings.
[b] The smoke shown by the movies were ranked as 1 through 30 with 1 being the least smoky and 30 being the smokiest firing.
[c] This test will be conducted when modifications (now in progress) to the facility are completed.
[d] The figures in parentheses indicate the number of motor firings that were averaged to obtain the listed values.
[e] An extinction of 1.6 represents a light transmission of 2.5% with a concomitant high measurement error. An extinction of ∞ represents a transmission of 0%. The values for RH-C-160 and RH-P-161 are therefore indistinguishable.

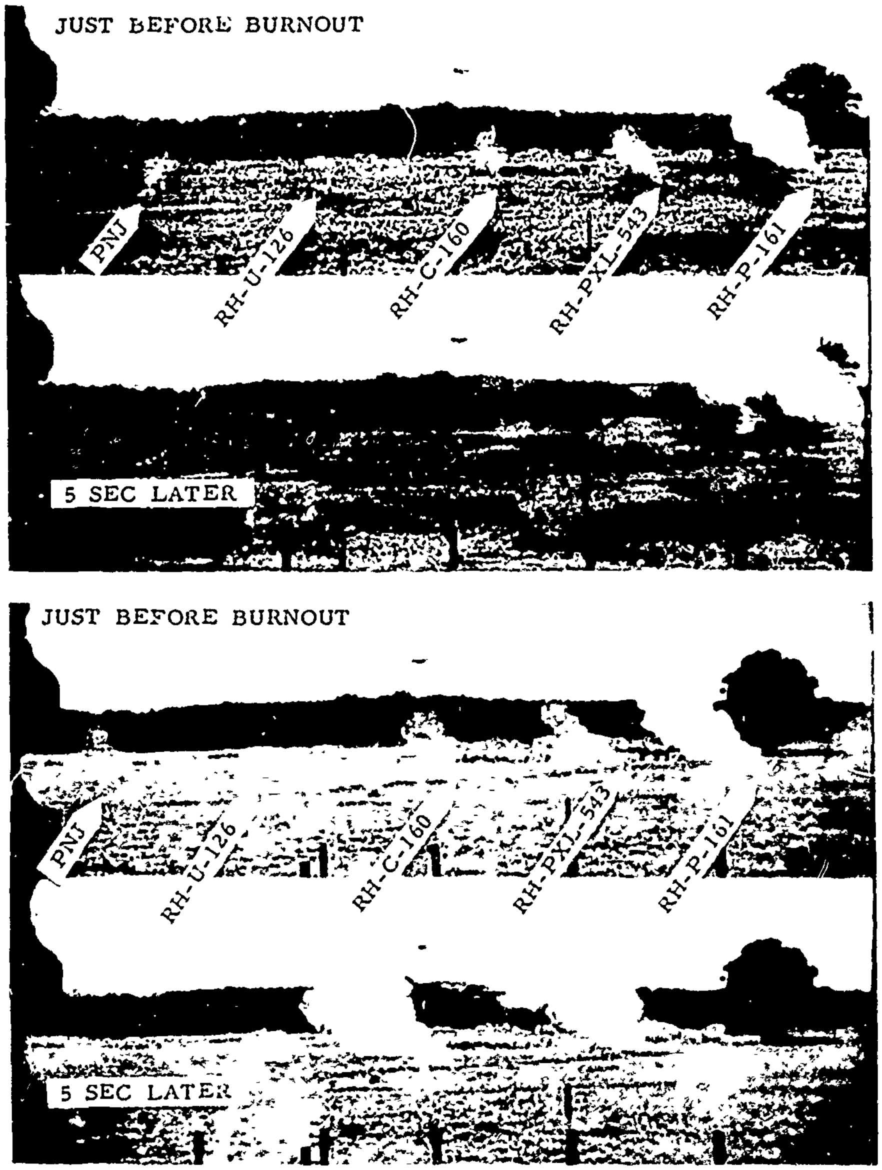

FIGURE 6. PHOTOGRAPHS OF THE SMOKE PRODUCED FROM 6.0 LB ROCKET MOTORS IN FIELD FIRINGS. CONDITIONS FOR THE UPPER PAIR ARE 87°F, 32% r.h.; FOR THE LOWER PAIR, 64°F, 84% r.h. LINOGRAPH SHELL-BURST PAN BLACK AND WHITE FILM WAS USED SINCE IT CLOSELY APPROXIMATES THE RESPONSE OF THE HUMAN EYE. NOTE THAT SMOKE DENSITY CONTINUES TO INCREASE AFTER BURN-OUT WITH SOME PROPELLANTS SUCH AS C-160. ALSO NOTE THE EFFECTS OF CONTRAST ON VISIBILITY AT THE TREE LINE

obtained where low (RH-U-126) and high (RH-C-100 at high humidities and RH-P-161) smoke densities were produced, but under intermediate conditions the relative rankings were mixed. These findings were in line with the findings discussed in the main text which showed that ballistic parameters such as mass discharge rate, residence time, etc., influence the amount of smoke produced; these, of course, change when scaling up from a 2-in. - to a 6-in. -diameter motor. Further, small motor data such as the different trends shown in tests with metal-containing propellant (RH-P-163) and the non-metallic propellant (RH-P-426) suggest that different scaling factors will be necessary for different types of propellant. A more thorough investigation of the ballistic parameters must be made before quantitative predictions of the smoke produced by large motor firings can be made on the basis of small motor test data.

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13. ABSTRACT

A systematic investigation of the effect of interior ballistic parameters on solid rocket propellant exhaust smoke was initiated in a controlled environment smoke measurement facility. Conventional plastisol nitrocellulose composite propellants were used in this investigation. Highly significant effects on exhaust smoke were found for varying interior ballistic parameters such as chamber pressure, mass discharge rate, and expansion ratio. These results are interpreted in terms of aerosol particle size and concentration as functions of time. Motors were prepared and fired outdoors to demonstrate the results of these studies under field conditions.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Smoke						
Interior ballistic parameters						
Signature (visual)						
AP-containing propellants						
Aluminum containing propellants						
Particle size						
Aerosol particle growth						